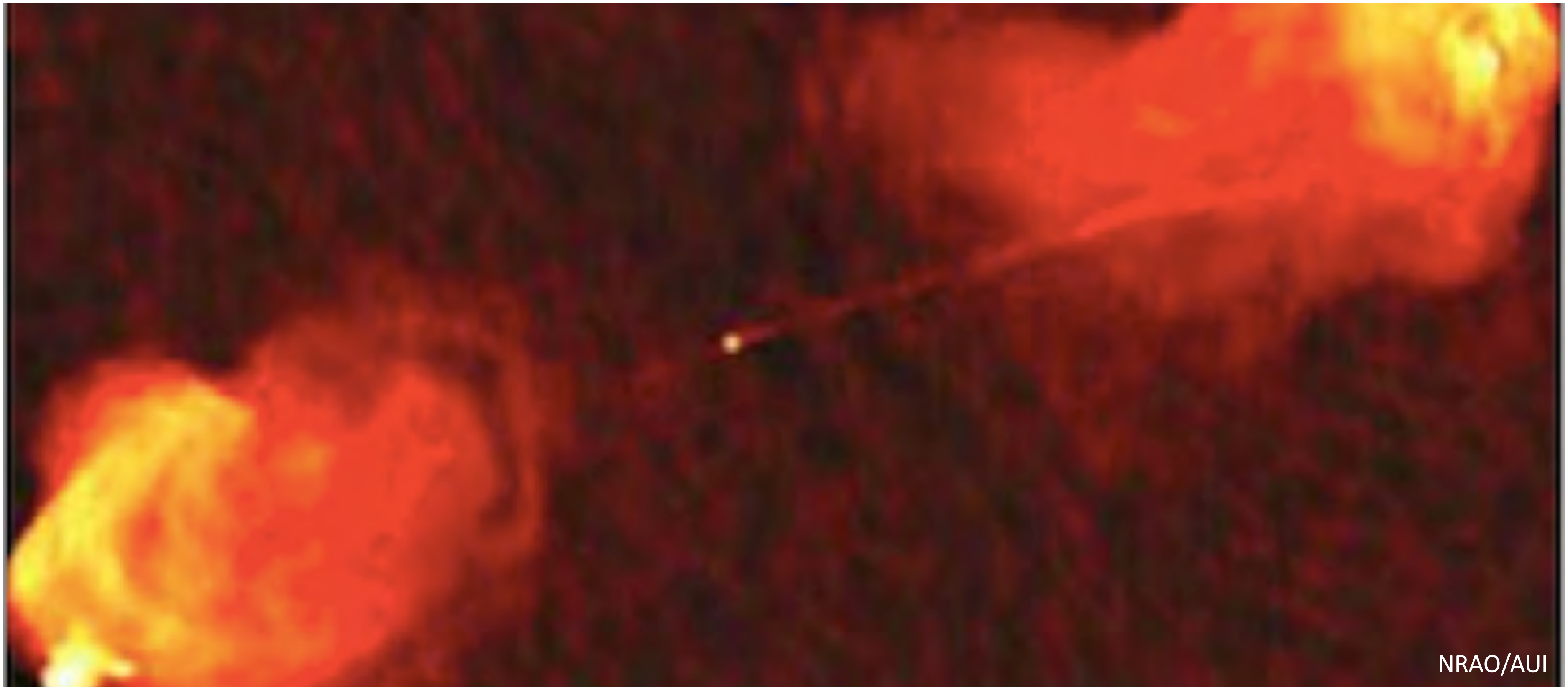
Plasma Accelerator Physics

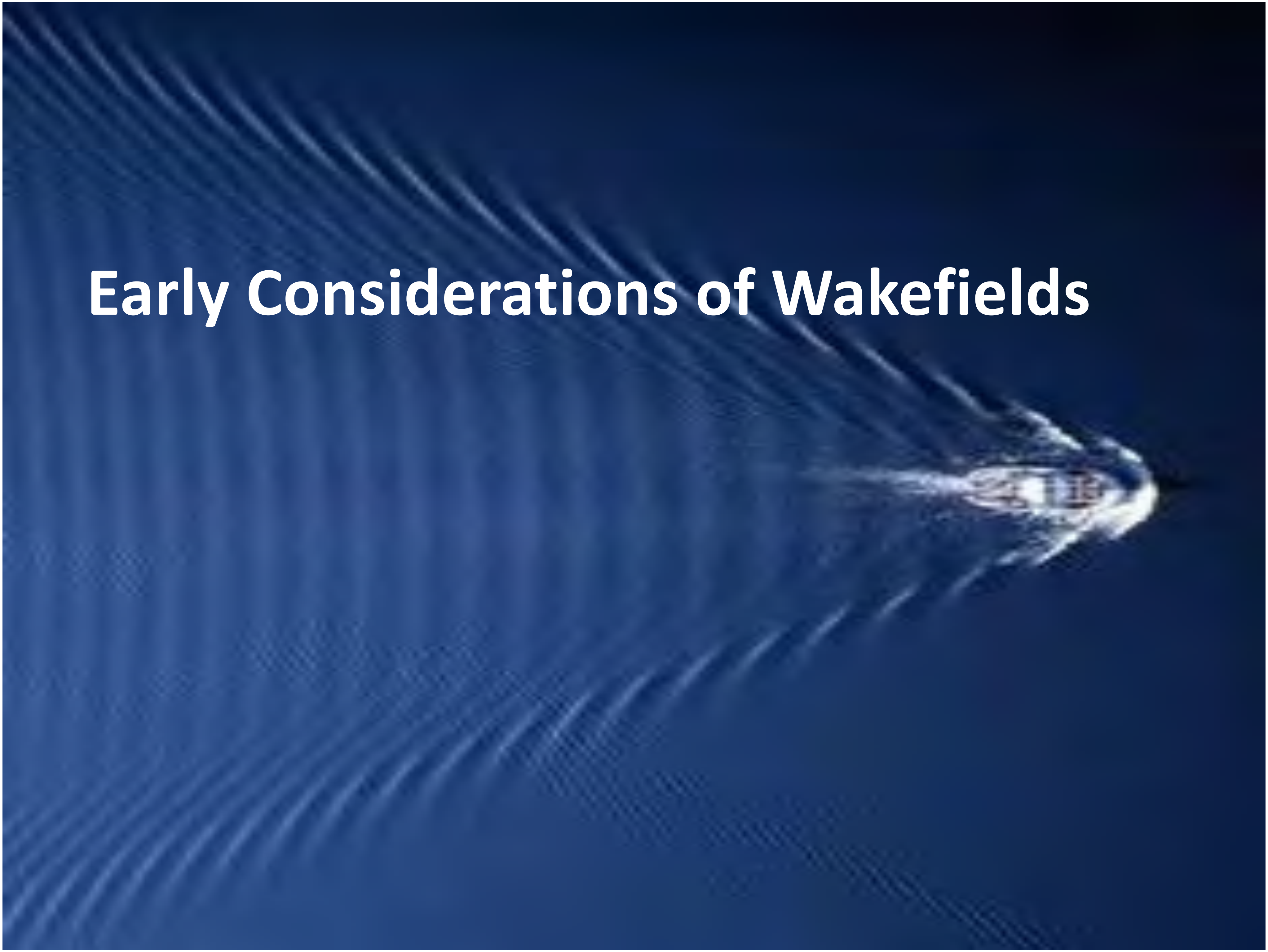
Toshiki Tajima, Norman Rostoker Chair Professor, UCI

Class 2:PHY249 (2021Fall)



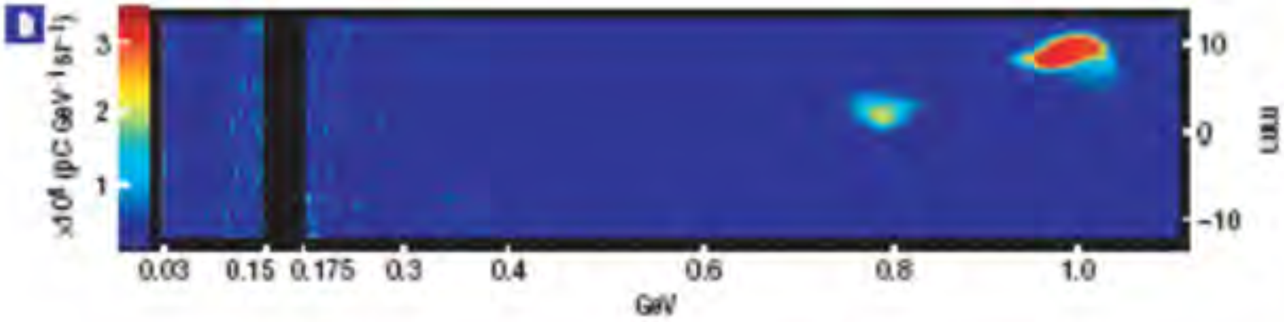
NRAO/AUI

Early Considerations of Wakefields



GeV electrons from a cm plasma

(empahsis by S. Karsch)



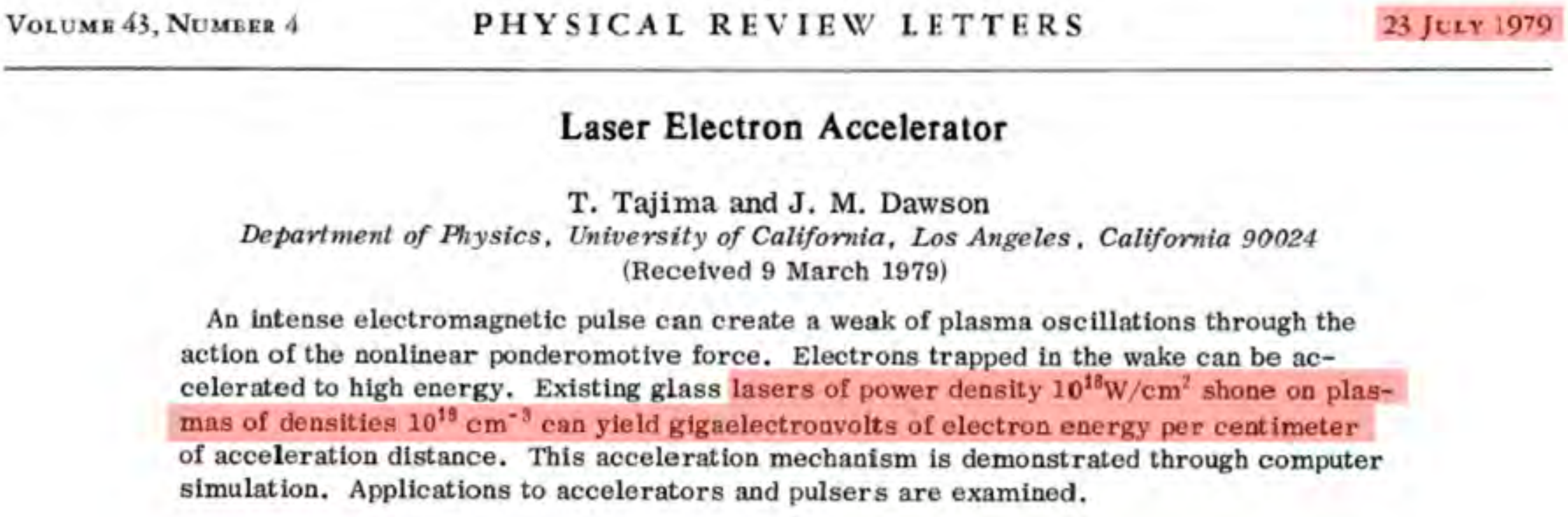
Leemans et al., Nature Physics, september 2006

310-μm-diameter channel capillary

P = 40 TW

density 4.3×10^{18} cm^{-3}.

laser intensity 10^{18} W/cm^2


VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Mourou: CPA invention (1985) (Nobel, 2018)

Toward Coherent Control of Wakefields:

Frequency-domain Holography

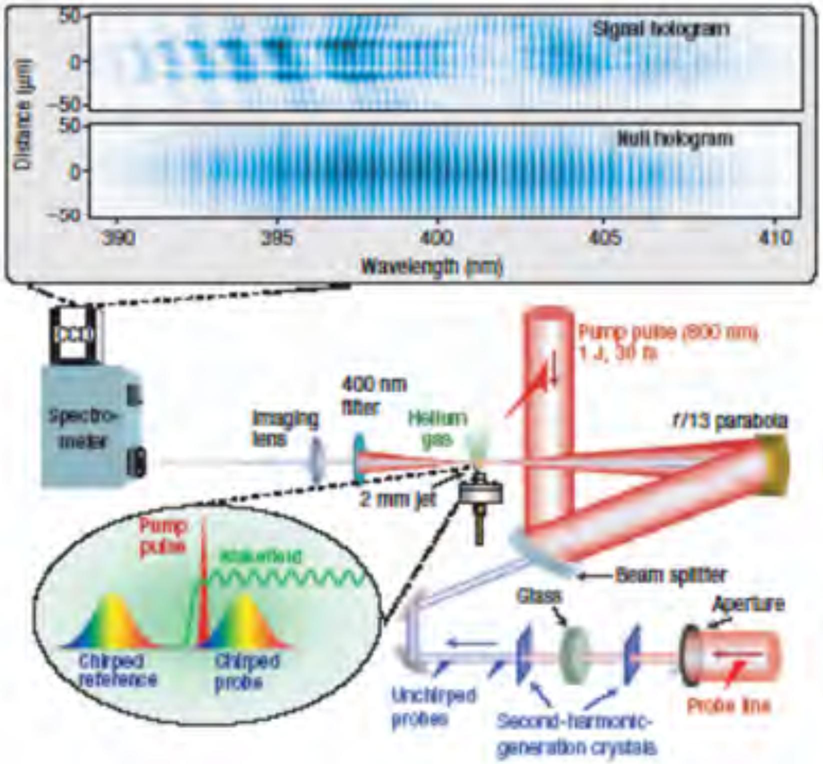
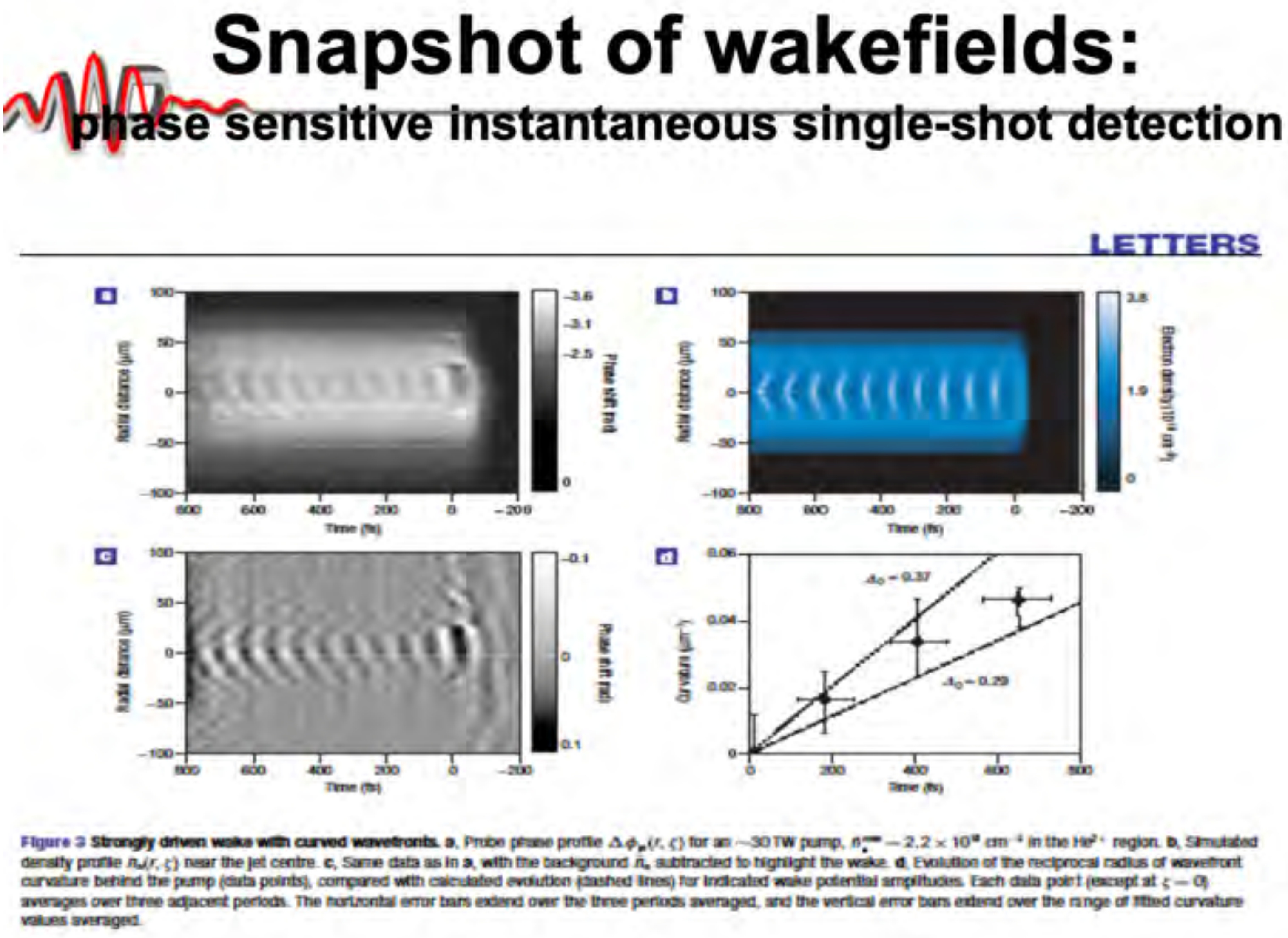


Figure 1 Experimental setup for FDH of laser wakefields. An f/13 parabola focuses an intense 30 fs pump pulse into a jet of helium gas, creating a plasma and laser wakefield. Two chirped, frequency-doubled 1 ps pulses, temporally synchronized and co-propagating with the pump, take holographic snapshots of the ionization front and wake. Phase alterations imposed on the trailing probe by these plasma disturbances are encoded in an FD interferogram, shown at the top with (upper) and without (lower) a pump, recorded by a charge-coupled-device camera at the detection plane of an imaging spectrometer. The wake structure is recovered by Fourier-transforming this data.

M.Downer (UTexas)

(Matlis et al.,2006)

Wakefield Observed in Lab



Snapshot of wakefields:

phase sensitive instantaneous single-shot detection

LETTERS

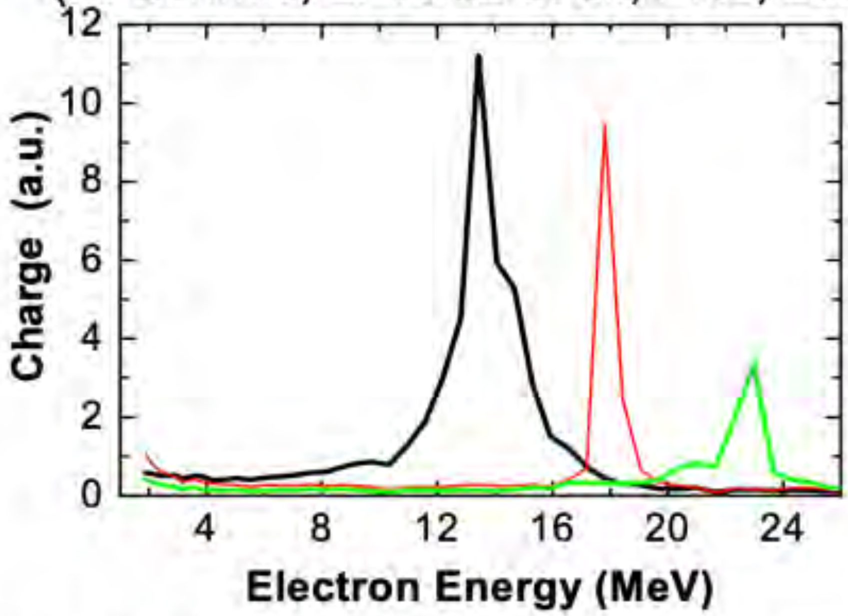
Figure 3 Strongly driven wake with curved wavefronts. a, Probe phase profile $\Delta\phi_{pr}(r,\zeta)$ for an ~30 TW pump, $n_e^{max} = 2.2 \times 10^{18}$ cm^{-3} in the He^{2+} region. **b**, Simulated density profile $n_e(r,\zeta)$ near the jet centre. **c**, Same data as in **a**, with the background $\bar{n}_e$ subtracted to highlight the wake. **d**, Evolution of the reciprocal radius of wavefront curvature behind the pump (data points), compared with calculated evolution (dashed lines) for indicated wake potential amplitudes. Each data point (except at $\zeta = 0$) averages over three adjacent periods. The horizontal error bars extend over the three periods averaged, and the vertical error bars extend over the range of fitted curvature values averaged.

(Matlis et al, 2006)

Example of LWFA efforts (1) @ LMU

Monoenergy electron spectra: from few-cycle laser (LWS-10)

(K. Schmid, L. Veisz et al., PRL, 2009)

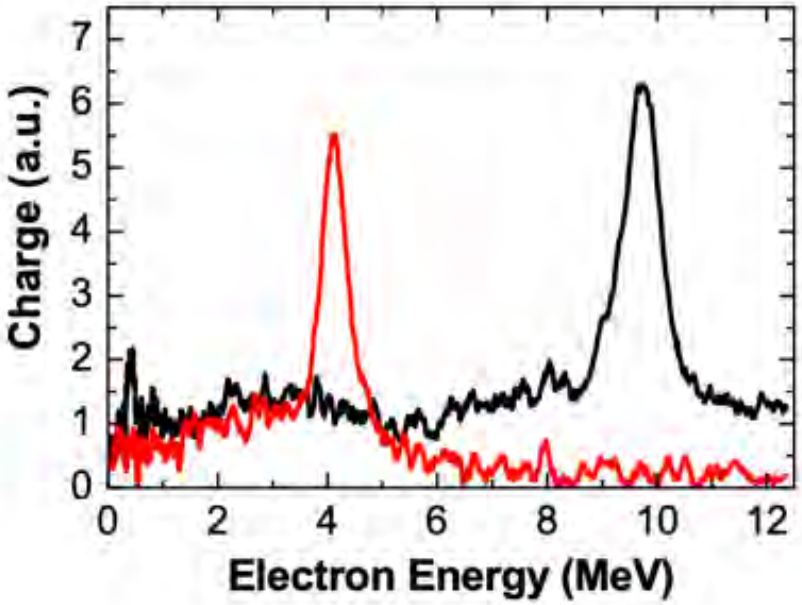


Large electron spectrometer 2 – 400 MeV

- **No thermal background !**
- **Energies: 13.4 MeV, 17.8 MeV, 23 MeV**
- **FWHM energy spread: 11%, 4.3%, 5.7 %**
- **~ 10 pC charge**

Small electron spectrometer:

- **Electron energies below 500keV**
- **No thermal background !**
- **4.1 MeV (14%); 9.7 MeV (9.5%)**

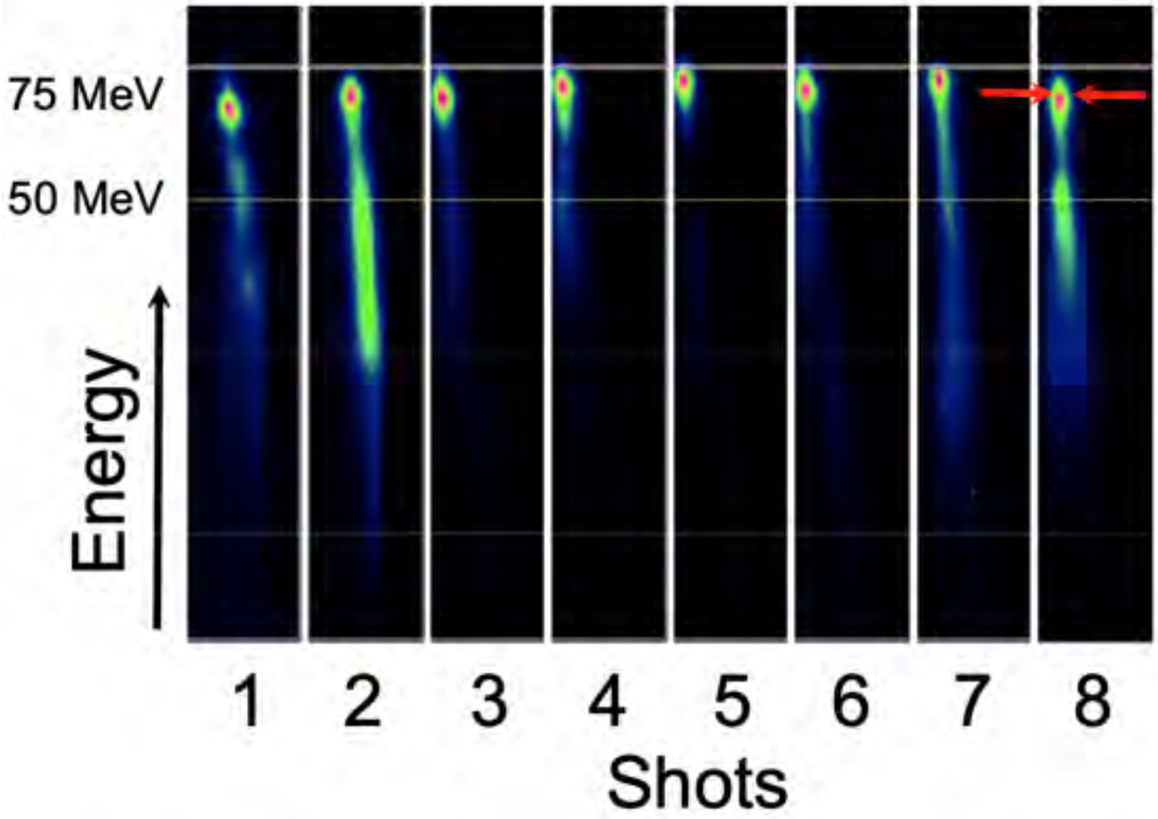


Effort (2)

Reproducible acceleration conditions

E ≈ 169.7 ± 2.0 MeV

1.1% peak energy fluctuation !



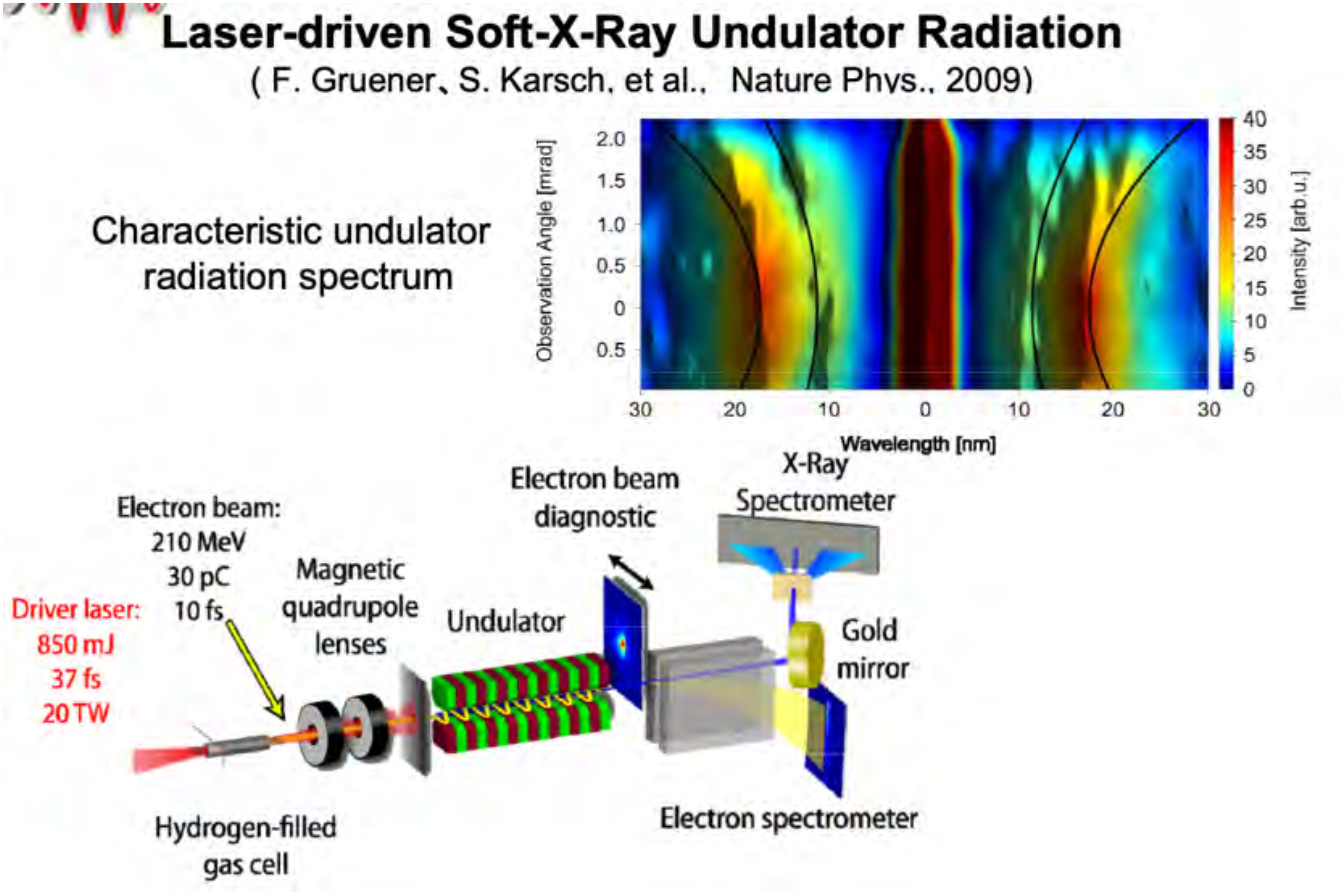
ΔE/E ≈ 1.76±0.26% RMS
→ Essential property for future table-top FEL operation

Source size image: provides emittance measurement, given the resolution can be improved

Electron trapping width
$v_{tr,e} \sim c\sqrt{a_0}$

(J. Osterhoff,…S. Karsch, et al., PRL 2008)

Effort part (3)

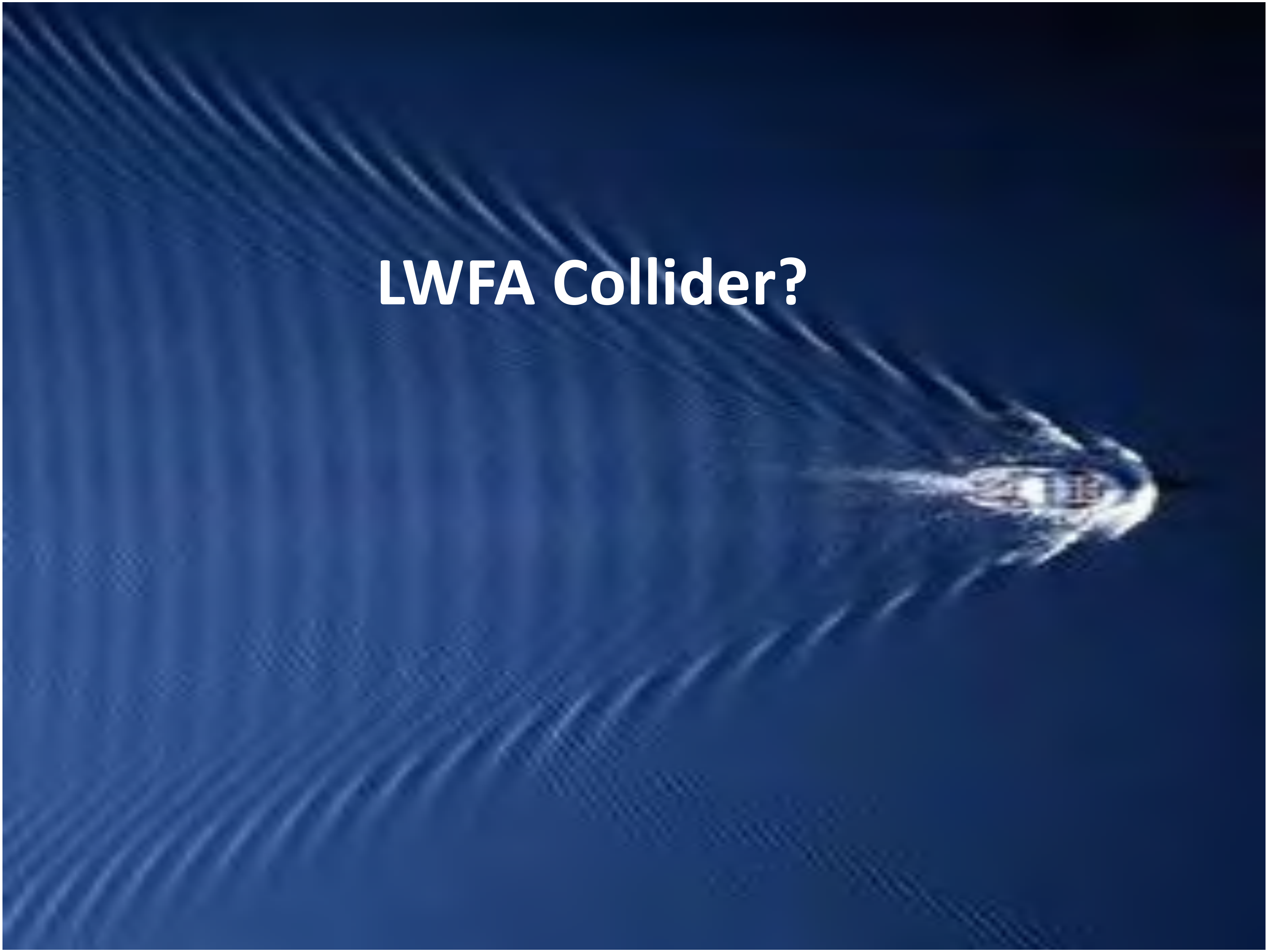


Laser-driven Soft-X-Ray Undulator Radiation

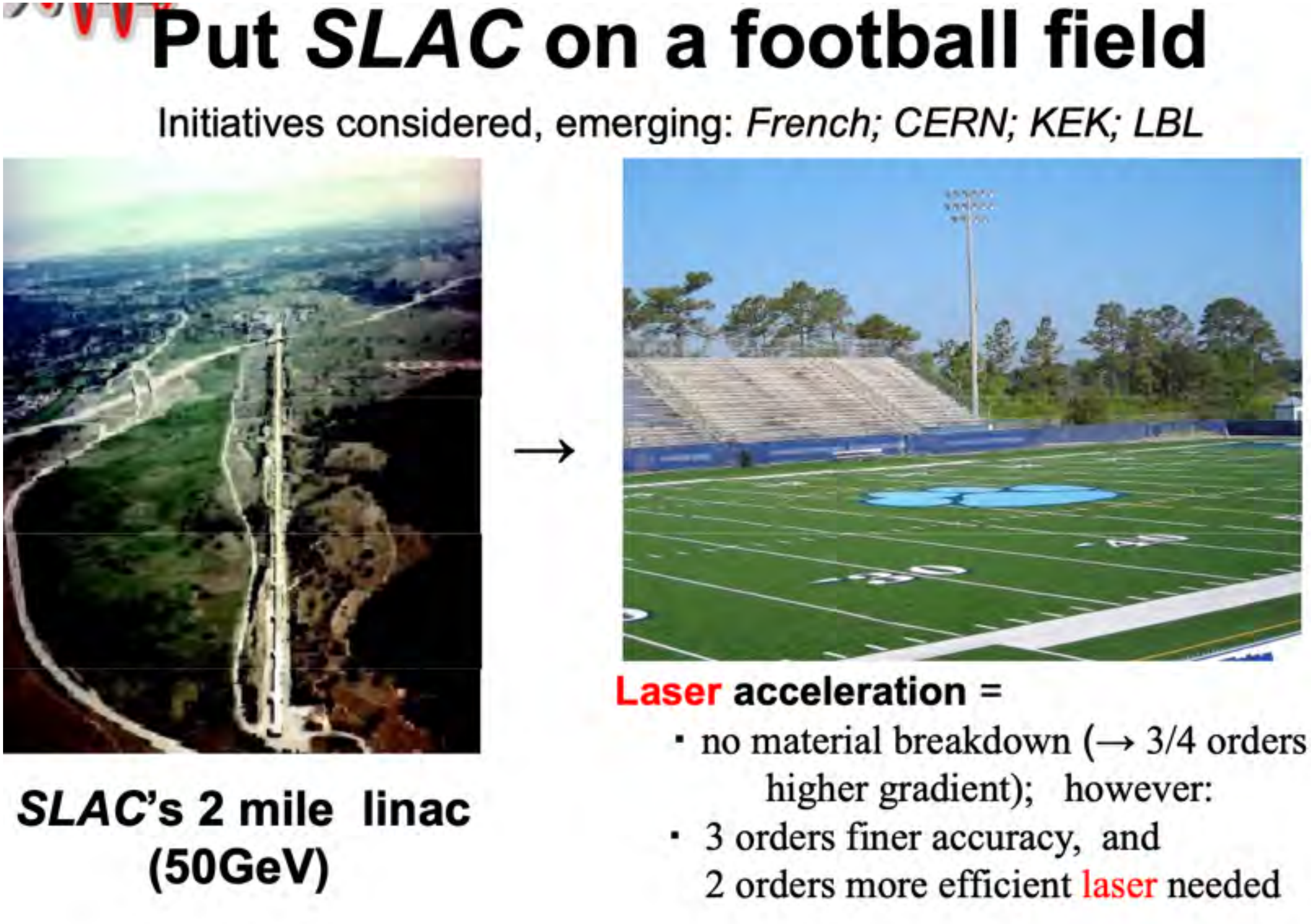
(F. Gruener, S. Karsch, et al., Nature Phys., 2009)

Characteristic undulator radiation spectrum

LWFA Collider?



Can we put several km onto a football field?



Put *SLAC* on a football field

Initiatives considered, emerging: *French; CERN; KEK; LBL*

→

***SLAC*'s 2 mile linac**
(50GeV)

Laser acceleration =

- no material breakdown (→ 3/4 orders higher gradient); however:
- 3 orders finer accuracy, and
  2 orders more efficient laser needed

Multi-staging (early bird)

(pre-CPA version)

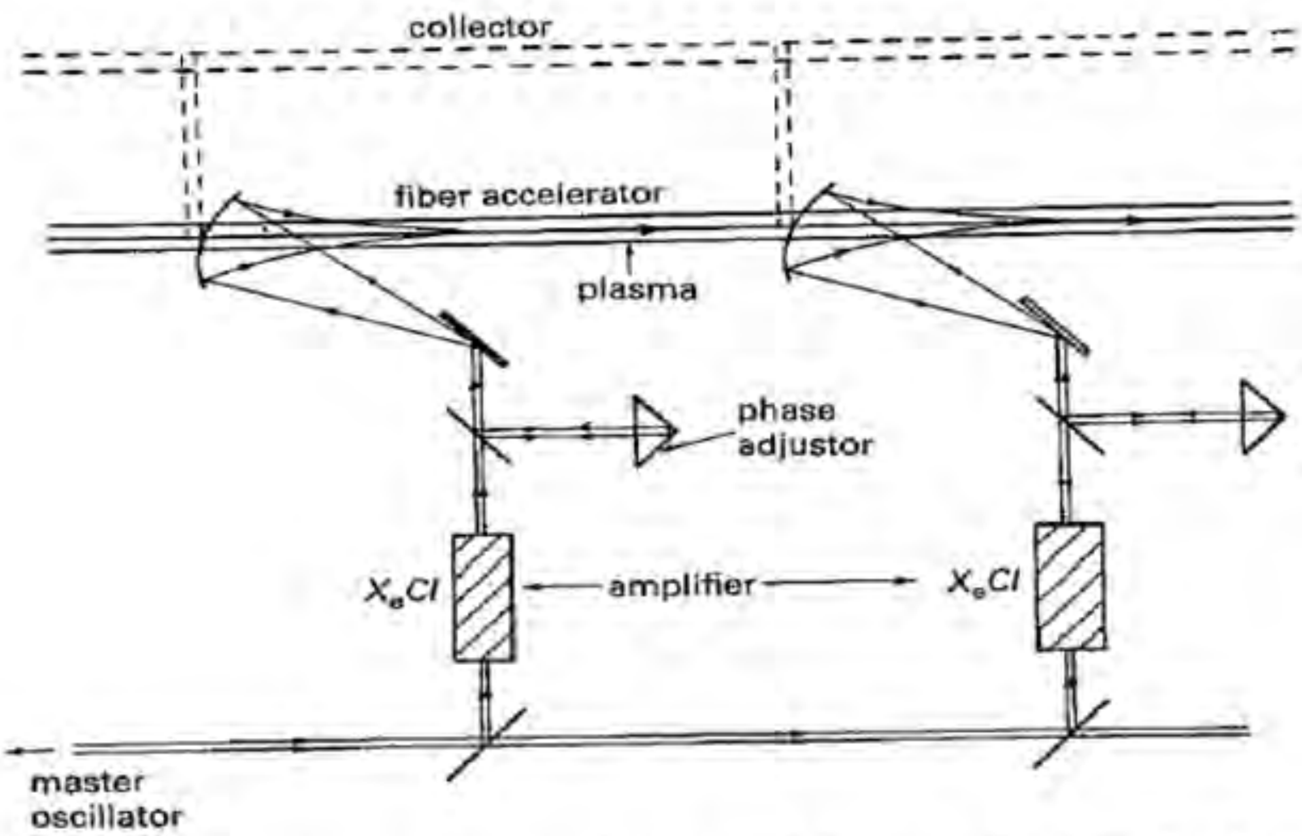


FIGURE 34. A conceptual plasma fiber accelerator with laser staging amplification *in situ*. The separation between the modules is characterized by the sum of the focal length and the pump depletion length. An example of X$_e$Cl lasers is taken.

(Tajima, Laser Part Beams,1985)

Early (1985) version of LWFA collider

Toward energy frontier (earliest version,1985) (3)

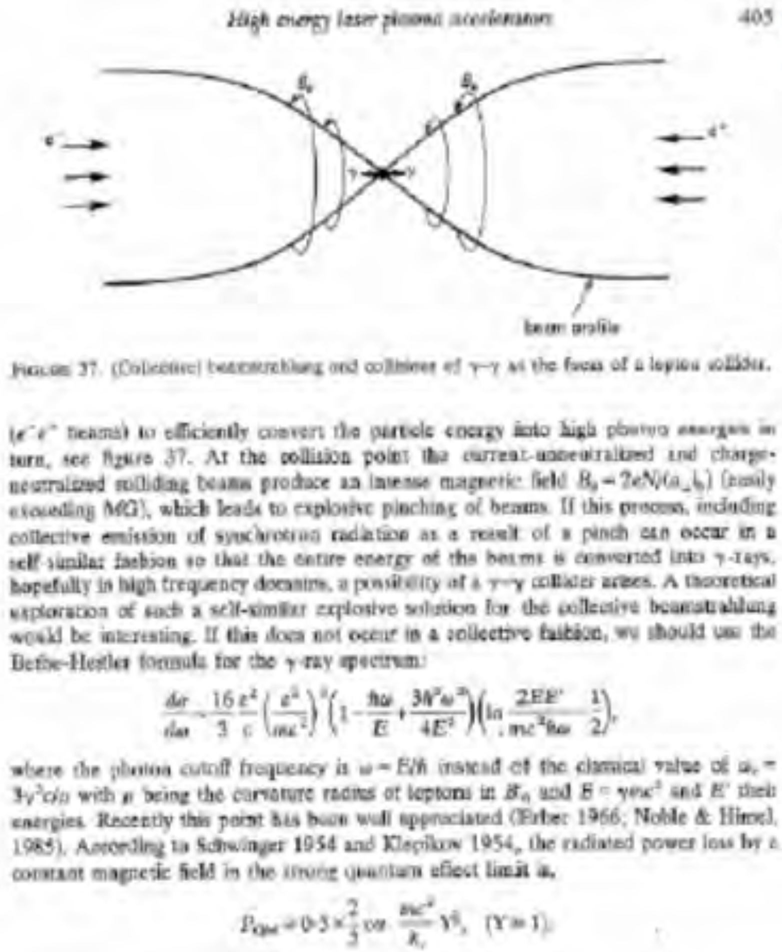


Figure 37. (Collective) beamstrahlung and collision of γ–γ at the focus of a lepton collider.

(e^-e^+ beams) to efficiently convert the particle energy into high photon energies in turn, see figure 37. At the collision point the current-unneutralized and charge-neutralized colliding beams produce an intense magnetic field $B_\theta = 2eN/(a_\perp l_b)$ (easily exceeding MG), which leads to explosive pinching of beams. If this process, including collective emission of synchrotron radiation as a result of a pinch can occur in a self-similar fashion so that the entire energy of the beams is converted into γ-rays, hopefully in high frequency domains, a possibility of a γ–γ collider arises. A theoretical exploration of such a self-similar explosive solution for the collective beamstrahlung would be interesting. If this does not occur in a collective fashion, we should use the Bethe–Heitler formula for the γ-ray spectrum:

$$\frac{d\sigma}{d\omega} = \frac{16}{3}\frac{e^2}{c}\left(\frac{e^2}{mc^2}\right)^2\left(1-\frac{\hbar\omega}{E}+\frac{3\hbar^2\omega^2}{4E^2}\right)\left(\ln\frac{2EE'}{mc^2\hbar\omega}-\frac{1}{2}\right),$$

where the photon cutoff frequency is $\omega = E/\hbar$ instead of the classical value of $\omega_c = 3\gamma^3 c/\rho$ with ρ being the curvature radius of leptons in B_θ and $E = \gamma mc^2$ and E' their energies. Recently this point has been well appreciated (Erber 1966; Noble & Himel, 1985). According to Schwinger 1954 and Klepikov 1954, the radiated power loss by a constant magnetic field in the strong quantum effect limit is,

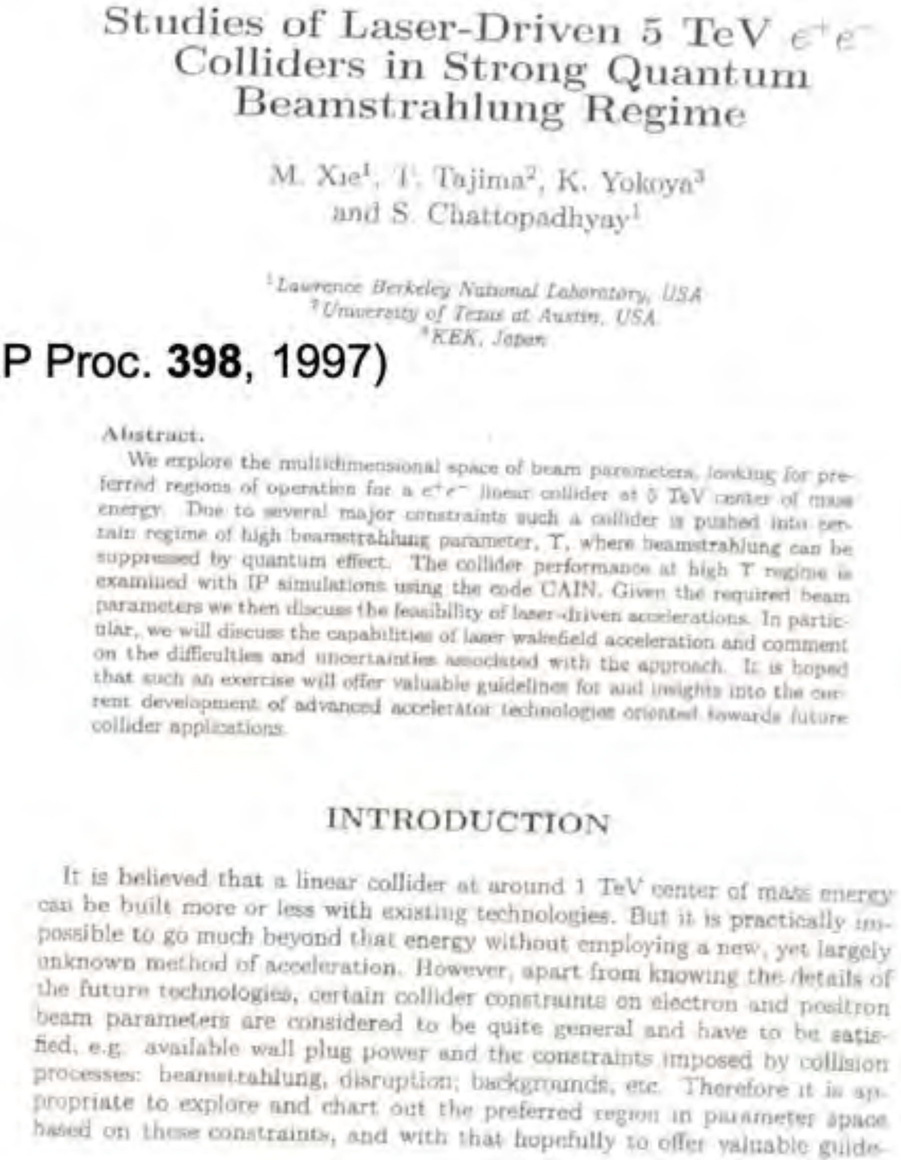
$$P_{QM} = 0\cdot 3 \times \frac{2}{3} c\alpha \frac{mc^2}{\lambda_c}\Upsilon^{2/3}, \quad (\Upsilon \gg 1).$$

Self-similar collision
(beamstrahlung)
toward ‘a point’ (enhanced
luminosity) possible?

→flat beam profile control

(Tajima, 1985)

Early bird of LWFA collider



Studies of Laser-Driven 5 TeV e^+e^- Colliders in Strong Quantum Beamstrahlung Regime

M. Xie[1], T. Tajima[2], K. Yokoya[3]
and S. Chattopadhyay[1]

[1] Laurence Berkeley National Laboratory, USA
[2] University of Texas at Austin, USA
[3] KEK, Japan

(AIP Proc. **398**, 1997)

Abstract.
We explore the multidimensional space of beam parameters, looking for preferred regions of operation for a e^+e^- linear collider at 5 TeV center of mass energy. Due to several major constraints such a collider is pushed into certain regime of high beamstrahlung parameter, Υ, where beamstrahlung can be suppressed by quantum effect. The collider performance at high Υ regime is examined with IP simulations using the code CAIN. Given the required beam parameters we then discuss the feasibility of laser-driven accelerations. In particular, we will discuss the capabilities of laser wakefield acceleration and comment on the difficulties and uncertainties associated with the approach. It is hoped that such an exercise will offer valuable guidelines for and insights into the current development of advanced accelerator technologies oriented towards future collider applications.

INTRODUCTION

It is believed that a linear collider at around 1 TeV center of mass energy can be built more or less with existing technologies. But it is practically impossible to go much beyond that energy without employing a new, yet largely unknown method of acceleration. However, apart from knowing the details of the future technologies, certain collider constraints on electron and positron beam parameters are considered to be quite general and have to be satisfied, e.g. available wall plug power and the constraints imposed by collision processes: beamstrahlung, disruption, backgrounds, etc. Therefore it is appropriate to explore and chart out the preferred region in parameter space based on these constraints, and with that hopefully to offer valuable guide-

With a plasma density of 10^{17}cm^{-3}, such a gradient can be produced in the linear regime with more or less existing T^3 laser, giving a plasma dephasing length of about 1 m [13]. If we assume a plasma channel tens of μm in width can be formed at a length equals to the dephasing length, we would have a 10 GeV acceleration module with an active length of 1 m. Of course, creating and maintaining a plasma channel of the required quality is no simple matter. To date, propagation in a plasma channel over a distance of up to 70 Rayleigh lengths (about 2.2 cm) of moderately intense pulse ($\sim 10^{15}$W/cm^2) has been demonstrated [14]. New experiment aiming at propagating pulses with intensities on the order of 10^{18}W/cm^2 (required for a gradient of 10 GeV/m) is underway [13].

Table 1. Beam Parameters at Three Values of Beam Power

CASE	P_b(MW)	$N(10^8)$	f_c(kHz)	ϵ_y(nm)	β_y(μm)	σ_y(nm)	σ_x(μm)
I	2	0.5	50	2.2	22	0.1	0.32
II	20	1.6	156	25	62	0.56	1
III	200	6	416	310	188	3.5	2.8

Table 2. Results Given By the Formulas

CASE	Υ	D_y	F_{oide}	n_γ	δ_E	n_p	$\mathcal{L}_g(10^{35}\text{cm}^{-2}\text{s}^{-1})$
I	3485	0.93	0.89	0.72	0.2	0.19	1
II	631	0.29	0.89	0.72	0.2	0.12	1
III	138	0.081	0.91	0.72	0.2	0.072	1

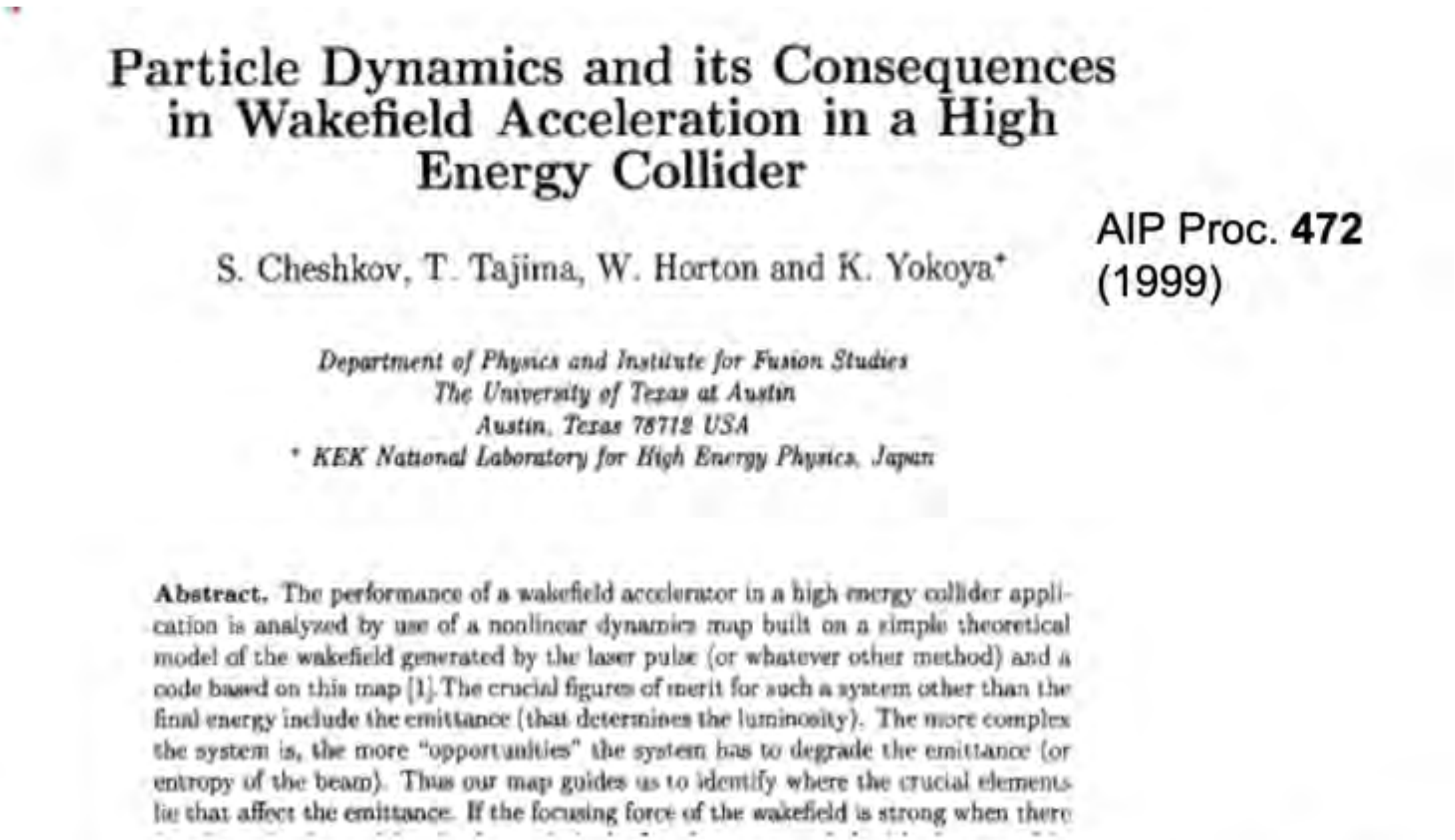
Table 3. Results Given By CAIN Simulations

CASE	n_γ	δ_E	σ_ϵ/E_0	n_p	$\mathcal{L}/\mathcal{L}_g(W_{cm} \in 1\%)$	$\mathcal{L}/\mathcal{L}_g(W_{cm} \in 10\%)$
I	1.0	0.38	0.42	0.28	0.83	1.1
II	0.97	0.26	0.36	0.12	0.65	0.80
III	0.84	0.21	0.32	0.06	0.62	0.75

Although a state-of-the-art T^3 laser, capable of generating sub-ps pulses with 10s of TW peak power and a few Js of energy per pulse [11], could almost serve the need for the required acceleration, the average power or the rep rate of a single unit is still quite low, and wall-plug efficiency inadequate. In addition, injection scheme and synchronization of laser and electron pulse from

Incorporated collider physics at collision point (beamstrahlung, Oide limit, etc.)

Early bird analysis of a collider



Particle Dynamics and its Consequences in Wakefield Acceleration in a High Energy Collider

AIP Proc. **472** (1999)

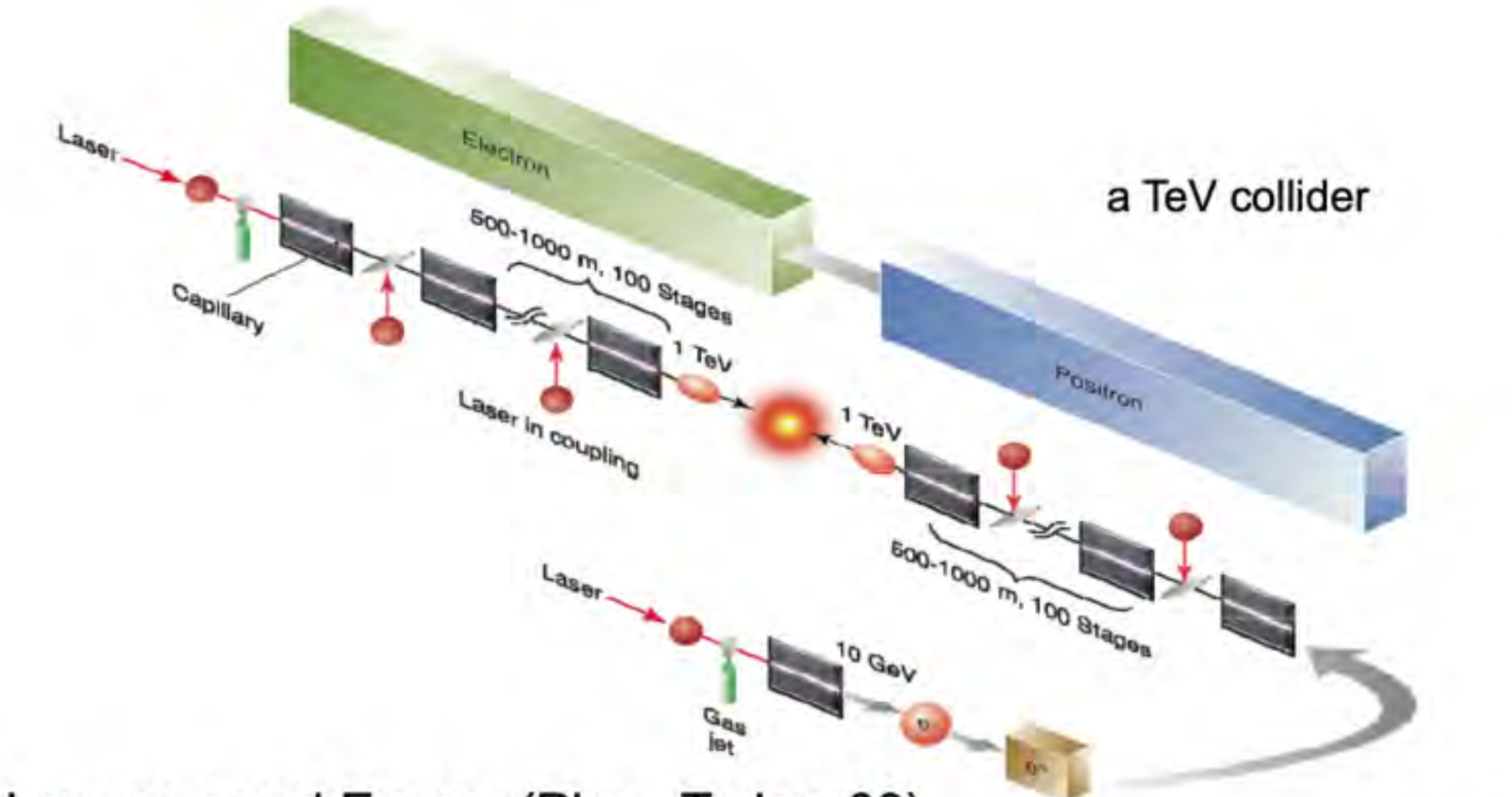
S. Cheshkov, T. Tajima, W. Horton and K. Yokoya*

Department of Physics and Institute for Fusion Studies
The University of Texas at Austin
Austin, Texas 78712 USA
* *KEK National Laboratory for High Energy Physics, Japan*

Abstract. The performance of a wakefield accelerator in a high energy collider application is analyzed by use of a nonlinear dynamics map built on a simple theoretical model of the wakefield generated by the laser pulse (or whatever other method) and a code based on this map [1]. The crucial figures of merit for such a system other than the final energy include the emittance (that determines the luminosity). The more complex the system is, the more "opportunities" the system has to degrade the emittance (or entropy of the beam). Thus our map guides us to identify where the crucial elements lie that affect the emittance. If the focusing force of the wakefield is strong when there

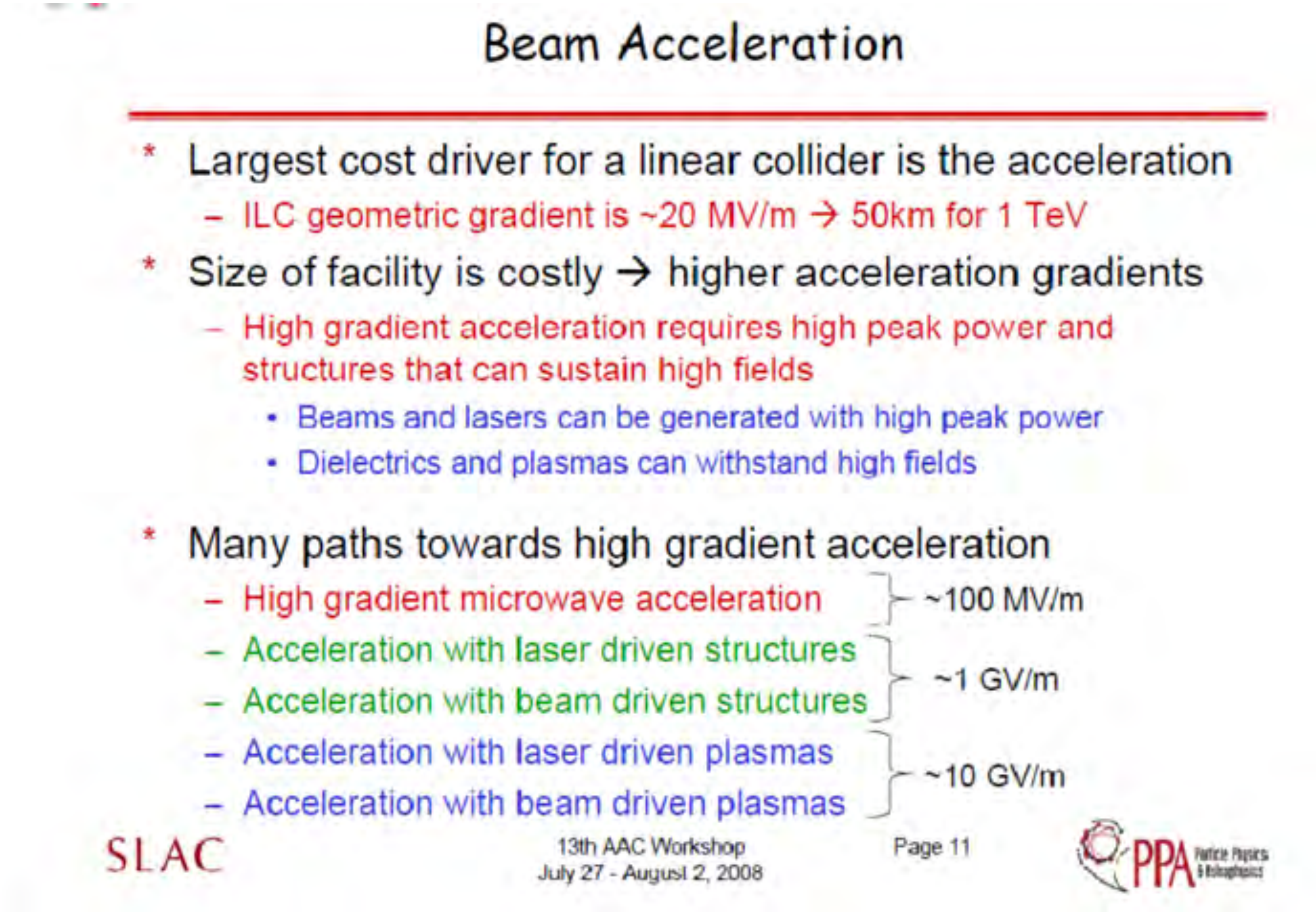
Transverse focusing/defocusing need to be mitigated. Plasma channel ideal

Later collider by LWFA



Leemans and Esarey (Phys. Today, 09)
ICFA-ICUIL Joint Task Force on Laser Acceleration(Darmstadt,10)

Some key issues of a collider



Beam Acceleration

- Largest cost driver for a linear collider is the acceleration
  - ILC geometric gradient is ~20 MV/m → 50km for 1 TeV
- Size of facility is costly → higher acceleration gradients
  - High gradient acceleration requires high peak power and structures that can sustain high fields
    - Beams and lasers can be generated with high peak power
    - Dielectrics and plasmas can withstand high fields
- Many paths towards high gradient acceleration
  - High gradient microwave acceleration
    ~100 MV/m
  - Acceleration with laser driven structures
  - Acceleration with beam driven structures
    ~1 GV/m
  - Acceleration with laser driven plasmas
  - Acceleration with beam driven plasmas
    ~10 GV/m

SLAC

13th AAC Workshop
July 27 - August 2, 2008

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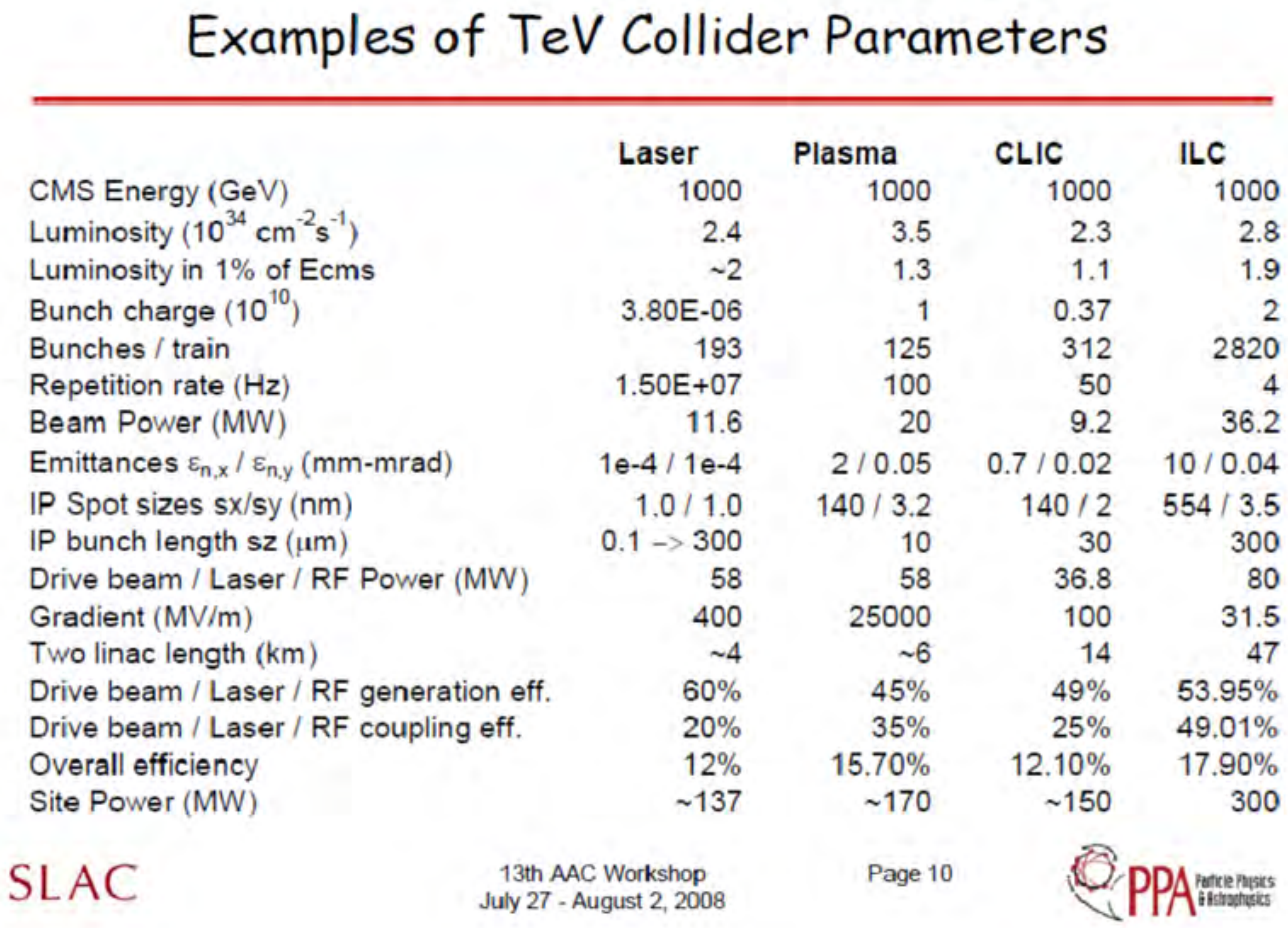
PPA Particle Physics & Astrophysics

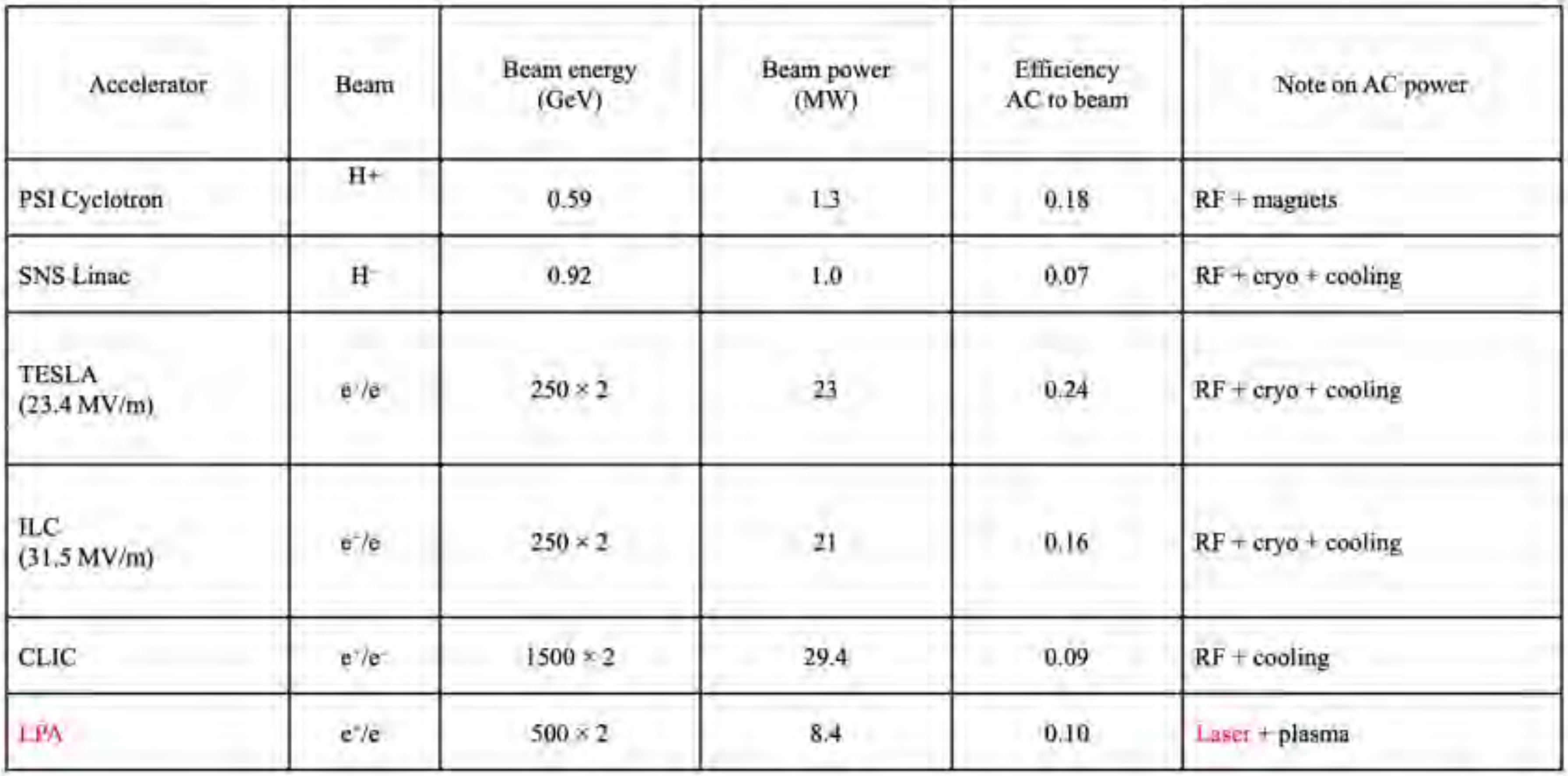
Future collider?



Examples of TeV Collider Parameters

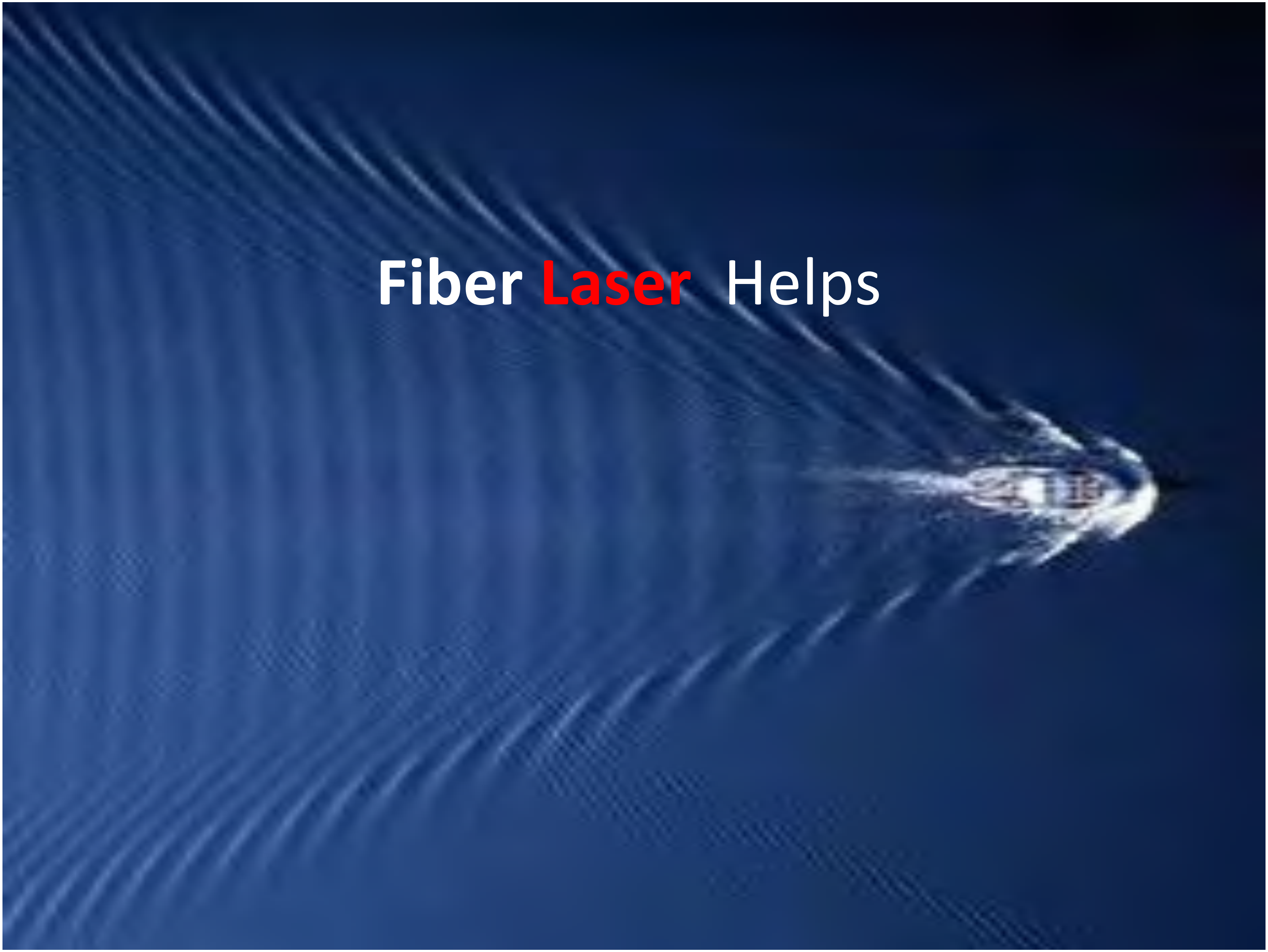
	Laser	Plasma	CLIC	ILC
CMS Energy (GeV)	1000	1000	1000	1000
Luminosity (10^{34} cm^{-2}s^{-1})	2.4	3.5	2.3	2.8
Luminosity in 1% of Ecms	~2	1.3	1.1	1.9
Bunch charge (10^{10})	3.80E-06	1	0.37	2
Bunches / train	193	125	312	2820
Repetition rate (Hz)	1.50E+07	100	50	4
Beam Power (MW)	11.6	20	9.2	36.2
Emittances $\varepsilon_{n,x}$ / $\varepsilon_{n,y}$ (mm-mrad)	1e-4 / 1e-4	2 / 0.05	0.7 / 0.02	10 / 0.04
IP Spot sizes sx/sy (nm)	1.0 / 1.0	140 / 3.2	140 / 2	554 / 3.5
IP bunch length sz (μm)	0.1 –> 300	10	30	300
Drive beam / Laser / RF Power (MW)	58	58	36.8	80
Gradient (MV/m)	400	25000	100	31.5
Two linac length (km)	~4	~6	14	47
Drive beam / Laser / RF generation eff.	60%	45%	49%	53.95%
Drive beam / Laser / RF coupling eff.	20%	35%	25%	49.01%
Overall efficiency	12%	15.70%	12.10%	17.90%
Site Power (MW)	~137	~170	~150	300

LW Collider vs conventional



Accelerator	Beam	Beam energy (GeV)	Beam power (MW)	Efficiency AC to beam	Note on AC power
PSI Cyclotron	H+	0.59	1.3	0.18	RF + magnets
SNS Linac	H^-	0.92	1.0	0.07	RF + cryo + cooling
TESLA (23.4 MV/m)	e^+/e^-	250 × 2	23	0.24	RF + cryo + cooling
ILC (31.5 MV/m)	e^+/e^-	250 × 2	21	0.16	RF + cryo + cooling
CLIC	e^+/e^-	1500 × 2	29.4	0.09	RF + cooling
LPA	e^+/e^-	500 × 2	8.4	0.10	Laser + plasma

Fiber **Laser** Helps

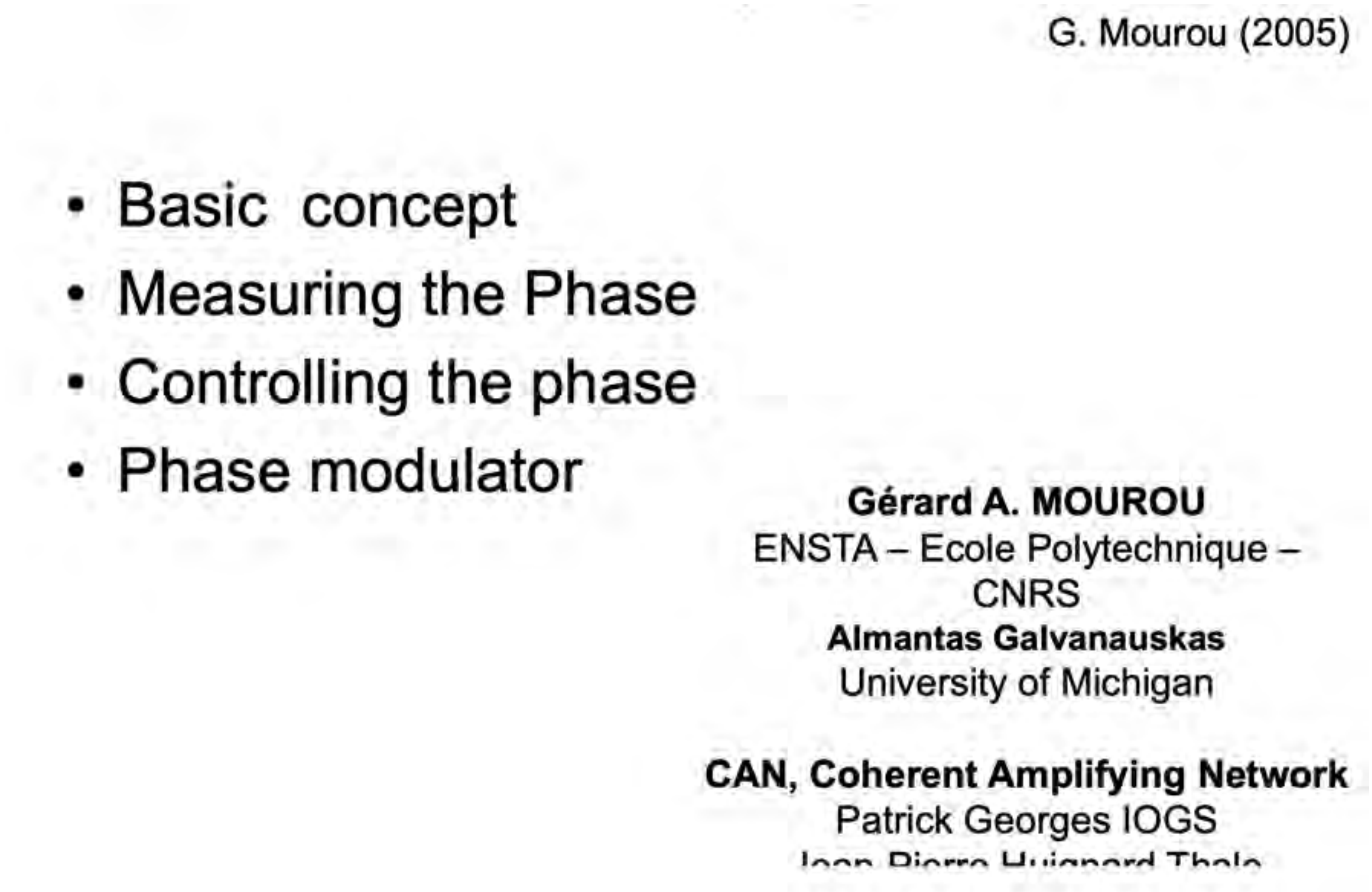


Mourou’s fiber laser motivation (CAN)

- High Gain fiber amplifiers allow ~ 40% total plug-to-optical output efficiency
- Single mode fiber amplifier have reached multi-kW optical power.
- large bandwidth (100fs)
- immune against thermo-optical problems
- excellent beam quality
- efficient, diode-pumped operation
- high single pass gain
- They can be mass-produced at low cost.

(G. Mourou)

Mourou’s fiber laser for collider



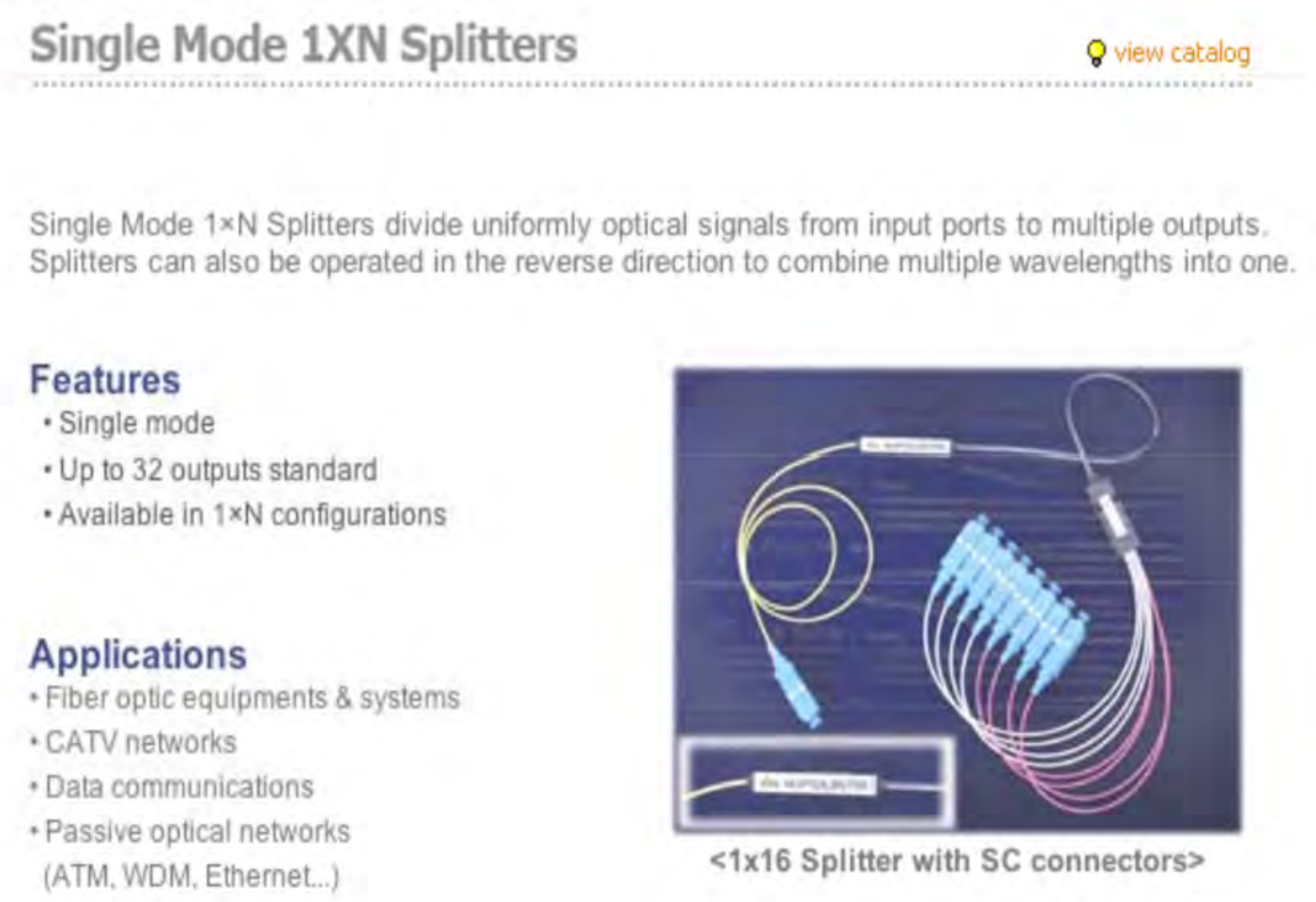
G. Mourou (2005)

- Basic concept
- Measuring the Phase
- Controlling the phase
- Phase modulator

Gérard A. MOUROU
ENSTA – Ecole Polytechnique – CNRS
Almantas Galvanauskas
University of Michigan

CAN, Coherent Amplifying Network
Patrick Georges IOGS
Jean Pierre Huignard Thale

Fiber laser



Single Mode 1XN Splitters

view catalog

Single Mode 1×N Splitters divide uniformly optical signals from input ports to multiple outputs. Splitters can also be operated in the reverse direction to combine multiple wavelengths into one.

Features

- Single mode
- Up to 32 outputs standard
- Available in 1×N configurations

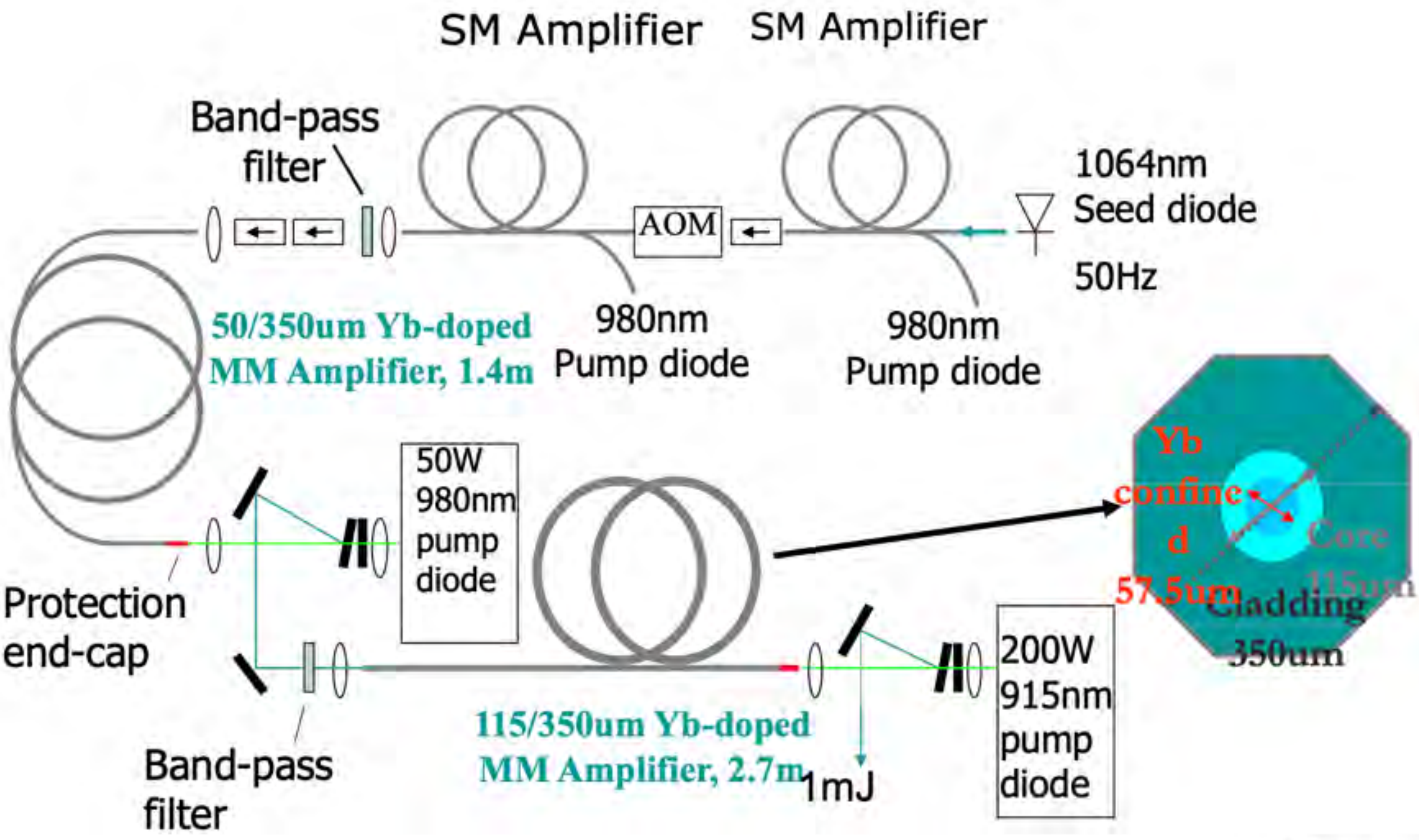
Applications

- Fiber optic equipments & systems
- CATV networks
- Data communications
- Passive optical networks (ATM, WDM, Ethernet...)

<1x16 Splitter with SC connectors>

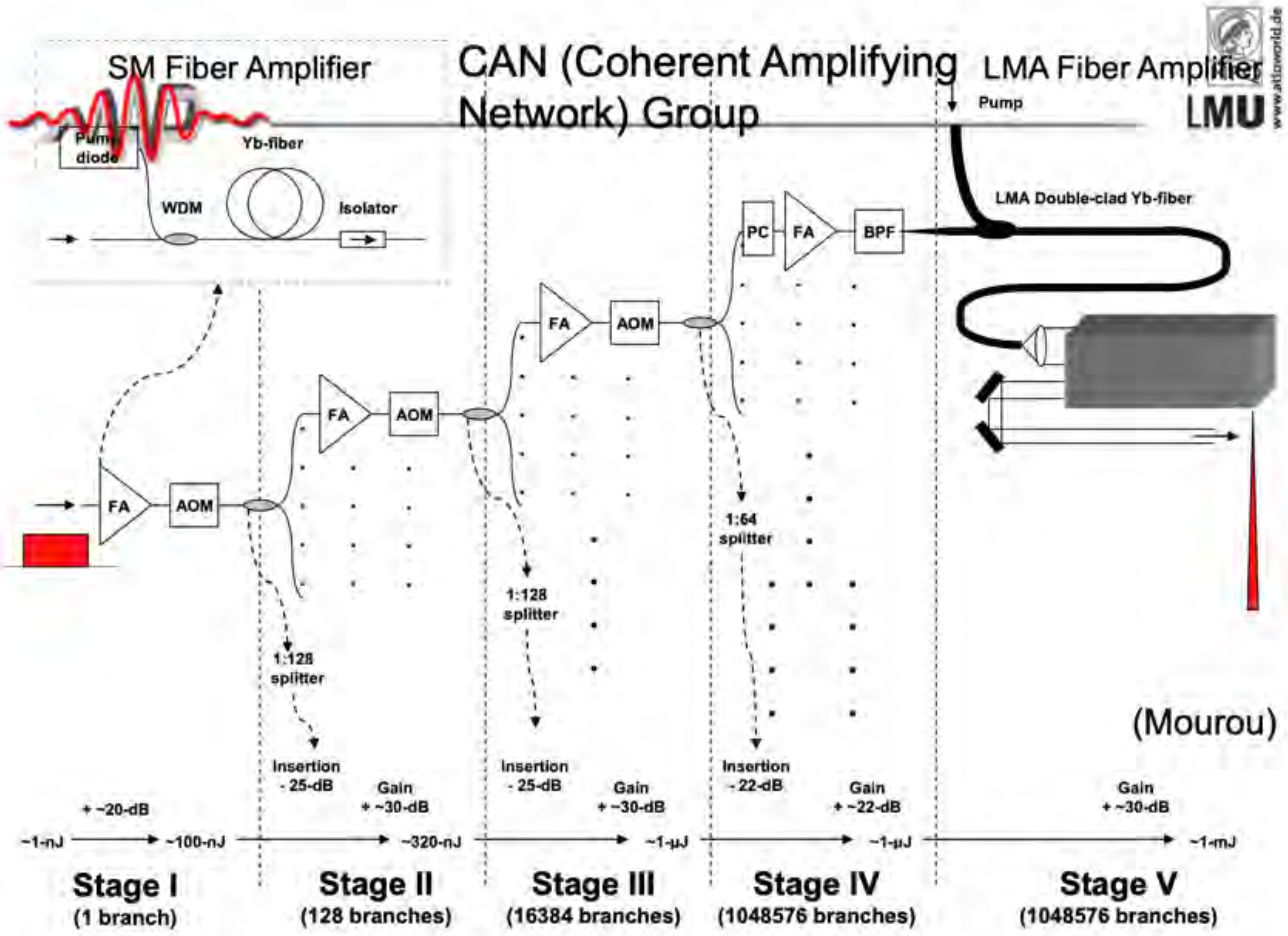
(mourou)

CAN (Coherent Amplification Network) of fiber lasers



(Mourou

CAN fiber laser (Mourou et al.)



Mourou, Tajima, et al. (2013)

G. Mourou's laser technology (fiber laser) vs. conventional

CLIC vs. Laser-Plasma

	CLIC	Laser Plasma (Fiber-based)
AC to RF/Laser	40%	40%
RF/Laser to beam	24%	20%
AC to beam	9.6%	8%

(Mourou)